Reply to comment by P. Olivier on "Preorogenic exhumation of the North Pyrenean Agly Massif (Eastern Pyrenees, France)"

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[1] We make this reply to Philippe Olivier's comments on the "conceptual model" proposed in our paper on the deformation of the Mesozoic cover of the northern Agly massif. He acknowledges that the observations, measurements, and interpretations of the macrostructures, microstructures, and the crystallographic preferred orientation of calcite are convincing. This was the core of our contribution; we therefore appreciate that our results are considered significant! As Olivier stressed, the model presented in the Discussion section is "conceptual"; this implies that we did not aim at representing the complete evolution, but merely a new tectonic framework in which the North Pyrenean massifs have evolved before the Pyrenean orogeny. Nobody is currently able to reliably reconstitute the preorogenic evolution of the Pyrenees. We therefore limited the graphic presentation of our model to a snapshot emphasizing tectonic features that, because they were grossly coeval (preorogenic), have almost certainly interacted during the rotation of Iberia relative to Eurasia. Our contribution highlights a widespread preorogenic deformation of the margin of Eurasia in the Eastern Pyrenees. This deformation was associated to a strong modification of the geotherm, responsible for the preorogenic "Pyrenean" metamorphism that reached peak temperature as high as 600°C in some Cretaceous basins [*Goldberg and Leyreloup*, 1990]. Simultaneous extensional tectonics at the southern and northern boundaries of the Agly Massif has certainly contributed to its exhumation. Such deformation may account for the exhumation of the other North Pyrenean Massifs and the subcontinental mantle. This extrapolation, however, requires to further investigate the deformation of the Mesozoic cover around the basement and peridotite massifs in the Northern Pyrenees.

[2] 1. "…The authors do not explain how sedimentation and metamorphism could be coeval, and how these events were dated here."

[3] Since the beginning of the 1990s, many publications have clearly highlighted the link between the formation of sedimentary basin in an extensional setting and the coeval development of ductile shear zones under metamorphic conditions beneath the basins. This proposition requires a mature extensional basin and lithosphere thinning, and is expected to result in sedimentation at the surface and synmetamorphic extensional deformation of the basin floor. For example, this is the case in the Caledonides of Norway [*Séguret et al.*, 1989, *Andersen and Jamtveit* 1990, *Andersen et al.* 1991, *Chauvet et al.* 1992] where systematic $^{40}Ar/^{39}Ar$ geochronology confirmed that sedimentation and extensional deformation within the basement were coeval and developed around 395 Ma, corresponding with the first deposit of the Devonian sediments [*Chauvet and Dallmeyer*, 1992]. In addition, *Séranne and Séguret* [1987] have observed a weak metamorphism associated with normal faulting developed at the base of the Devonian sediment. More recently, the occurrence of synextension intrusive rocks was observed by *Andresen et al.* [2007] and considered as an evidence of syn-extension metamorphism within basement rocks.

[4] For major rifts, it is clear that the middle/lower crust beneath the basins deforms ductilely. During extentional crustal thinning the isotherms move closer to the surface, with the result that the brittle-ductile transition propagates upwards and may reach sediments deposited at the early stage of the basin opening.

[5] As indicated in our article, formation of the North Pyrenean Basins was triggered by the rotation of Iberia relative to Europe during the early stages of North-Atlantic formation, between 120 and 80 Ma [e.g., *Choukroune*, 1992; *Sibuet et al.*, 2004]. The age of the preorogenic metamorphism of the Northern Pyrenees has been consistently estimated between 110 and 85 Ma [*Albarède and Michard-Vitrac*, 1978; *Golberg et al.*, 1986; *Montigny et al.*, 1986]. A possible westward decrease in age was suggested by *Albarède and Michard-Vitrac* [1978], and ages

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in the range 90–105 Ma, corresponding to the Albian-Cenomanian, would be more likely for the eastern domain. The preorogenic metamorphism was related to the lithosphere thinning induced by the rotation of Iberia. It was associated with seawater transfer through the crust that advected heat efficiently in the Mesozoic sediments [*Goldberg and Leyreloup*, 1990]. This evolution was not instantaneous and lasted several million years. In the Northern Pyrenees, the upward propagation of the isotherms was facilitated by hot seawater percolating through the sediments and advecting heat.

[6] To complement this answer after modification of the comment by Olivier, we would stress that we never suggested that "sedimentation and metamorphism of the Albian marls could be coeval." Citing several authors, we said that the development of the basins and the metamorphism were coeval.

[7] 2. "The authors consider that the Boucheville syncline corresponds to a single basin [the 'Boucheville basin'] formed during the Albian time on the southern border of the uplifting Agly Massif (section 2 and Figure 13)…"

[8] The focus of our work was not on the sedimentology of the Cretaceous basins, but on the deformation of the lower part of the Mesozoic cover north of the Agly basement massif. To integrate our data in a more comprehensive conceptual model, we referred to previously published work, for instance on the Boucheville Basin, without entering into too much detail. We did not claim that the Agly basement was unroofed during the Cretaceous, but that the Agly Massif underwent exhumation. However, it is difficult to argue for a continuity between the southern, metamorphic (>500°C) [*Goldberg and Leyreloup*, 1990] Boucheville Basin and the unmetamorphosed Cretaceous formations of the St. Paul syncline north of the Agly Massif. Indeed, even west of the Agly Massif, where the Boucheville and St. Paul synclines are almost in contact, they are, however, separated by a major tectonic contact that involves mantle peridotites (Salvezines peridotites). They also display a strong contrast; the Cretaceous south of the major contact is strongly metamorphic and unmetamorphosed north of the contact. This suggests that these two domains were initially rather far from each other. In the hypothesis that they have been in continuity, they were anyway in significantly different tectonic settings. Finally, these observations imply that the Eocene-Oligocene shortening between Iberia and Eurasia has concealed rather large domains that initially separated the Boucheville and St. Paul Basins.

[9] 3. "The authors considering that the age of the northward décollement of the Agly cover is Albian, they conclude (section 6.2) that this fact is contradictory with previous interpretations admitting that the Albian basins were formed as pull-apart basins linked to an E-W-trending left-lateral movement between Iberia and Europe…"

[10] Olivier misunderstood our point of view on the pull-apart model of opening of the Cretaceous basins in the North Pyrenees. Indeed, we did not question this model because of the age of the deformation recorded in the northern Agly extensional shear zone. We merely emphasized two problems with this model:

a. "The consistent N- to NE-trending lineations observed in the Mesozoic limestone north of the Agly basement massif are not in agreement with the deformation expected in pull-apart basins formed along the North Pyrenean Fault."

[11] The extension expected from the pull-apart basins model would be oriented close to NW (see for instance *Choukroune* [1992] and references therein). Lineations in the northern Agly extensional shear zone are significantly oblique to this direction and are difficult to integrate into this model. However, evidence of synmetamorphic, NW trending extension exists in other domains of the Northern Pyrenees [e.g., *Clerc*, 2012] and we therefore concluded that more data are required to evaluate which is the best tectonic model to account for basins opening.

b. "However, the new data from the Agly Massif suggest that the Late Cretaceous extension affected a large domain of the Eurasian margin and this does not fit well the 'pull-apart basins' model."

[12] As Olivier wrote, evidence of extensional, synmetamorphic deformation was recorded in a wide area north of the Agly basement massif, especially considering that this area was subsequently shortened during the Pyrenean orogeny. Such a wide extensional domain on the Eurasian margin is also difficult to reconcile with pull-apart basins developed along the North Pyrenean Fault as suggested by *Choukroune and Mattauer* [1978]. We however do not favor any model at present. We consider that the processes of basins opening during the rotation of Iberia are not fully understood and that additional data, especially on the preorogenic deformation and its relationships with the exhumation of the lower crust and lithospheric mantle should be collected and then integrated in a fully consistent model.

[13] 4. Olivier's fourth issue concerns the existence of an intra Paleozoic shear zone along the contact between the Ordovician metasediments that form the upper part of the Agly basement and the gneisses that form the lower part. This is clearly a subsidiary aspect of our article since we did not perform a detailed analysis of the deformation of basement rocks. A jump in metamorphic conditions is obvious at the contact between the two domains, suggesting that the Precambrian-Paleozoic basement has been thinned during an extensional event [e.g., *Paquet and Mansy*, 1991]. Several generations of shear zones can be observed in the basement; they have formed under different temperature conditions. In some of them, deformation occurred under temperature high enough for quartz to be totally recrystallized as large new grains displaying a clear crystallographic fabric. However, most shear zones formed under low-temperature conditions, just above the brittle-ductile transition for quartz and in the field of brittle behavior for feldspars, i.e., a temperature of ~300–350°C, depending on the strain rate. As stated in our article, in these LT mylonites (see Figure 3b), quartz frequently did not recrystallize and forms monocrystalline ribbons or, when recrystallized, the new grains are less than 10 µm in size and their crystallographic orientation remains very difficult to measure even using the EBSD technique. We therefore decided to not refer to the data published in *Olivier et al.* [2004] since they mix low- and high-temperature mylonites and are thus not entirely reliable.

[14] 5. The significance of the breccia formations along the North Pyrenean Zone is a crucial problem, but in our opinion,

it is not directly relevant to the subject of our article. Several types of breccia are distributed along the belt and some of them are indeed assigned to the latest Cretaceous or early Tertiary since they stratigraphically overlie the metamorphic Mesozoic sediments. The so-called Baixas breccia (eBr as labeled on the BRGM geological map) outcrops along the hinge of the Bas Agly southern anticline. They are mainly composed of clasts of Mesozoic metasediments, mostly marbles, including fragments of scapolite-bearing Albian metamorphic flysch. We consider that these breccias are not directly related to the process of crustal thinning addressed in our paper and consequently, we did not mention them. According to previous studies, these breccias are considered to be deposited in a compressional setting well after the development of the Cretaceous basins, either during the Late Cretaceous or during the Eocene [e.g., *Mattauer and Proust*, 1965]. Since these breccias contain very little material originating from the erosion of the continental basement such as Paleozoic metamorphic or plutonic rocks, this supports that the sedimentary cover has not been totally eroded before the Late Cretaceous. The repartition of the metamorphic Mesozoic sequences in the eastern Agly [see Figure 2 in *Vauchez et al*., 2013] suggests that at the end of the extensional deformation, it was still covering most if not all of the Agly basement occurred. This does not imply that the crust has not been extremely thinned beneath the metamorphic Mesozoic cover. In our interpretation, we consider that the lower crust has been exhumed but not necessarily unroofed. We should, however, recognize that the cartoon in Figure 13 of our article may suggest that unroofing of the Agly basement occurred. This however does not modify the main conclusions derived from our results.

[15] 6. We are glad that at this stage of his comment, Olivier acknowledges "the authors show that the ductile deformation of the base of the lower Agly syncline happened at rather high temperature (in a 337–387°C range) and that, consequently, this deformation is coeval with the metamorphism." The author therefore finally concedes that the data presented in our paper substantiate that the ductile extensional deformation of the northern Agly Mesozoic sequence was coeval with the pre-orogenic metamorphism.

[16] Regarding his remark that this deformation has been observed at the western termination of the lower Agly syncline where the Mesozoic formations "are not clearly metamorphic (no characteristic mineral)," we disagree with this statement. The points 30 and 11 on the map of Figure 2 mark the observations made in the Lower to Middle Jurassic *marmorized* limestones involved in the syncline. Point 29 is in Devonian marmorized limestones at the contact with the syncline. These limestones have been plastically deformed and have a crystallographic preferred orientation similar to those observed in samples from the eastern part of the syncline. They have been deformed under temperature conditions high enough to allow dislocation creep, dynamic recrystallization, and diffusion. Such temperatures are higher than those recorded during the Pyrenean orogeny. In addition, there is a structural homogeneity from the eastern to the western part of the Agly syncline. The foliation and lineation are similar all along the syncline and folded by the Pyrenean event. Evidence of ductile shearing is not limited to the vicinity of Eocene thrust contact; it affects a large part of the Agly syncline. *Goldberg and Leyreloup* [1990] have shown that the syn-kinematic to late-kinematic crystallization of specific minerals, especially scapolite, was possible only in domains percolated by "sea-water" fluids.

[17] We do apologize for being imprecise in using epochs from the international geologic timescale. Indeed, the North Pyrenean Basins are usually referred to as "Albian-Cenomanian basins" (see for instance *Choukroune* [1992]). The extension responsible for opening started in the Albian, which is Early Cretaceous and continued during the Cenomanian, i.e., the Late Cretaceous. The frontiers are sometimes confusing, especially when geodynamic processes do not respect them.

[18] Finally, Olivier's conclusion "the Alpine evolution of this part of the Pyrenees is still poorly constrained…" does not contribute much to a better understanding of the preorogenic processes active in the Pyrenees. We however converge on one point: more data is needed, especially on the preorogenic deformation (timing, conditions, processes) of the the North Pyrenean basement and peridotite massifs and of their Mesozoic cover.

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